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Final Report

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Engineering and Environmental Sciences Division
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13. ABSTRACT (Maximum 200 words)

The research work under this contract studied turbulence structures in the atmospheric boundary layer by focussing on microfronts. Microfronts are zones of sharp gradients which occur at the leading edge of wind gusts and upstream edges of thermals. The present work indicates that microfronts also result from convergence zones induced by horseshoe vortices and longitudinal roll vortices. The microfronts and their parent eddy structures account for the majority of the flux in the boundary layer, and in cases of strong winds, contribute to wind damage and structural fatique. However, existing methods, such as Fourier spectra, cannot be used to study microfronts which are local and aperiodic. In fact, microfronts and boundary layer eddies have been traditionally studied in terms of subjective conditional sampling. To avoid this subjectivity, we have developed objective techniques to study atmospheric turbulence from the microfront point of view. These include new methods for computing spectra and filtering data. The techniques developed in this work have then been used to study coherent structures and their transport in the atmospheric boundary layer.

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STATEMENT OF PROBLEM

The research work under this grant studied turbulence structures in the atmospheric boundary layer by focussing on coherent structures and microfronts. Microfronts are zones of sharp gradients which occur at the leading edge of wind gusts and upstream edges of thermals. The present work indicates that microfronts also result from convergence zones induced by horseshoe vortices and longitudinal roll vortices. The microfronts and their parent eddy structures account for the majority of the flux in the boundary layer. However existing methods, such as Fourier spectra, cannot be used to study microfronts which are local in real space and aperiodic. Microfronts and boundary layer eddies have been sometimes studied in terms of *subjective* conditional sampling. The present research has developed more objective techniques to study atmospheric turbulence from the microfront point of view. The techniques developed in this work have then been used to study coherent structures and their transport in the atmospheric boundary layer.

SUMMARY OF IMPORTANT RESULTS

1. Introduction

Much of the preliminary work was carried out in the Ph.D. thesis of Nimal Gamage [1]. He demonstrated that the Haar transform could be used to more effectively study coherent structures which are local in space and contain sharp zones of strong gradients. He developed a preliminary version of the Haar filter. He also developed an experimental numerical model using basis sets with built in sharp edges (here the Walsh basis). Additional work on the proper choice of scaling of the Wavelet transform for estimating spectral peaks is discussed in detail in Gamage and Hagelberg [5].

The Haar transform is sometimes criticized by Wavelet purists for being discontinuous and lacking compactness in Fourier space. Neither of these shortcomings are of concern for our studies because we are interested in maximum compactness in physical space and are applying the transform to discrete data. The simplicity and economy of the Haar transform are additional advantages. However the real purpose of this work is not technique development but rather improved understanding of the structure of boundary-layer eddies. Where a significant fraction of the motions were wave-like, we relied upon conventional Fourier decomposition [2].

2. A study of coherent structures, scaling laws and microfronts using different decompositions

We have examined the relationship between coherent structures and scaling laws.

Toward this goal, we analyzed atmospheric observations of turbulence collected 45 m above a flat surface during the Lammefjord Experiment in Denmark. These observations represent more than 40 hours of strong wind conditions and constitute the longest time series of nearly stationary conditions known to us.

To study the robustness of the scaling laws, the time series of velocity fluctuations are decomposed into Fourier modes, the local Haar basis set and eigenvectors of the lagged covariance matrix sometimes referred to as empirical or proper orthogonal functions [3,6-8]. Turbulent eddies are local and nonperiodic so that the usual Fourier decomposition into Fourier modes can be physically ambiguous as a consequence of Heisenberg's uncertainty principal. A principal advantage of the wavelet transform is localization where the spacing of the transform decreases with decreasing scale. That is, small scale features are decomposed with finer spatial resolution compared to large scale features. Here we choose the Haar function to focus on regions of sharp changes.

The decompositions are first applied to 1680 samples of phase locked coherent structures centered about eddy microfronts [6]. The microfronts are relatively ubiquitous narrow zones of strong horizontal gradients. The samples are about 400 m wide, occupy about 40% of the total record and explain the majority of the Reynolds stress. For comparison, a second set of samples are selected with random phase. The eigenvector and Haar decompositions are able to partially separate the small scale variances due to the coherent eddy microfronts from that due to the fine scale structure with random phase. In the Fourier spectrum, both of these contributions to the variance appear together at the higher wavenumbers and their individual contributions cannot be separated. Even though the sharp gradients lead to changes which are coherent on the larger scales, they contribute to the high wavenumber energy in the Fourier decomposition and therefore influence the overall slope of the Fourier spectrum . This effect is relatively minor for the scale distribution of energy but exerts an important influence on higher moment statistics.

For all three decompositions, the first mode extracts most of the spatial inhomogeneity associated with the phase locked structure. Intermediate and smaller scale modes mainly represent variance with random phase and approximately obey Kolmogorov -5/3 scaling for the distribution of energy with scale within the inertial subrange. Therefore this scaling law is observed in spite of the phase locked inhomogeneity and is robust with respect to choice of basis set. The eigenvector decomposition most effectively captures the phase locked structure with the fewest modes. The higher order eigenvectors become similar to Fourier modes with random phase. Deviations from the -5/3 scaling are observed to be slight and depend on the exact scaling region and choice of basis set. Therefore, deviations from -5/3 scaling are not robust with respect to the basis set.

The microfronts strongly influence the higher order statistics such as the 6th order structure function traditionally used to estimate the energy transfer variance or dissipation variance. The intermittency of fine scale structure, energy transfer variance and dissipation are not completely characterized by random phase, as often assumed, but are partly associated with microfronts characterized by systematic phase with respect to the coherent structures.

The Fourier and Haar spectrums were also computed for the entire record. The peak of the Haar energy spectrum occurs at smaller scales compared to that of the Fourier spectrum. The Haar transform is local and emphasizes the width of the events. The Fourier spectrum peaks at the scale of the main periodicity, if it exists, which includes the spacing between the events.

Other orthonormal wavelet bases, in addition to the Haar bases, can be applied. However in terms of the spectral energy distribution for our data, we found that the choice of the wavelet basis set was not as important as the local character of the basis functions as contrasted to the global nature of the Fourier basis set [6].

In contrast to analysis of well-developed turbulence, data representing turbulence in the strongly stratified case is appropriately analyzed in terms of the Fourier basis set as in [2]. Here the flow is strongly influenced by gravity waves which lend themselves to Fourier decomposition. The resulting Fourier spectra for the strongly stratified case observed in the Lammefjord Experiment are discussed in [2].

3. Flux decomposition into coherent structures

Since the momentum flux is dominated by the coherent structures containing the microfronts, we have studied the momentum flux associated with the samples selected by applying the Haar transform to the Lammefjord data [4]. The vertical and horizontal velocity components in these structures are approximately 180 deg out of phase, leading to efficient downward transfer of horizontal momentum. At the 45 m tower level, such coherent structures are observed with a typical width of 500 m. Samples were further decomposed in terms of the eigenvectors of the lagged covariance matrix. The first eigenvector of the coherent structures accounts for most of the flux by filtering out noisier smaller scale motions without smoothing the microfront zones of sharp changes.

The coherent structures explain more of the record flux than the velocity variances, reflecting the event nature of the fluxes. The large momentum flux associated with the gust microfronts is due to the strong longitudinal velocity fluctuations and the significant correlation between longitudinal and vertical velocity fluctuations. On scales significantly larger than 500 m, large-amplitude variations of the longitudinal velocity component ("inactive turbulence") are only weakly correlated to the weak vertical motions which leads to little momentum flux. With surface heating, the vertical and horizontal velocity fluctuations become systematically phase-lagged, leading to inefficient momentum transport [4].

Taking advantage of the domination of the fluxes by the coherent gust microfronts, a new technique for estimating record sampling problems was developed (*the coherent structure method).*

4. The constant variance Haar filter

To formally partition the turbulent flow into coherent structures and smaller scale turbulence without conditional sampling, we have separated the signal into low pass and high pass filtered parts. Conventional low pass filters with fixed response functions (weighting functions) are normally used to remove noise or natural small scale variance. Unfortunately, such filters also smooth sharp features of interest such as microfronts or edges of thermals.

Our work [8] constructed a low pass filter by first decomposing the signal into an orthogonal Haar basis set consisting of different scales (dilations) and locations (translations) of the Haar function. We specify the *amount of variance to be retained* in which case the minimum scale passed by the filter varies with position as dictated by the local nature of the signal. For example, small scale variance is automatically passed by the filter at the microfront while small scale variance is removed between the microfronts. As a result, the filter retains sharp local edges (microfronts) associated with the coherent structure but removes small scale noise with random phase.

In regions of action or sharp changes, the constant variance filter retains more modes and therefore includes smaller scales. In regions of less variation, the filter automatically retains fewer modes, that is, most of the variance can be captured with only the larger scale modes. A version of this filter with less phase problems can be constructed by first forming the reconstruction independently in overlapping "reconstruction windows". These reconstructions are composited at each point of the original record by averaging all of the reconstruction windows covering that point.

The filter applied to the Lammefjord data [8] does indeed remove small scale variations yet preserves most of the sharpness of the coherent sharp changes and retains the general asymmetry of the coherent structures. A sudden increase of flow speed associated with a microfront is retained without significant smoothing, even though most of the random fluctuations on the scale of the microfront thickness are removed by the filter. The filtered signal also includes a few small scale events which make a significant contribution to the total variance. That is, the specified variance method allows some variations which are coherent only on the small scales, if the event is of sufficiently large amplitude to explain an important fraction of the total variance.

5. Relation of microfronts to horseshoe vortices

We are conditionally sampling microfronts from direct eddy simulations of weakly stratified shear flow [9]. The microfronts and their three dimensional environments are studied by conditionally sampling cubes about the microfront based on an offset Haar transform. The microfronts occur throughout the numerical domain and are systematically related to outflows from horseshoe vortices. The latter are the principal coherent structures generated in these simulations. While the results appear to provide an important three-dimensional link between microfronts and coherent structures, considerable refinement work is required.

6. Two-dimensional structure using multiple towers

We are studying the propagation of microfronts using the three towers from the Lammefjord experiment for the strong wind case where the flow is directed approximately along the line containing the towers. The Haar transform method of conditional sampling was refined to include a de-jittering procedure by consulting the transform simultaneously at different dilations.

The results indicate that the microfront, on average, advances at a speed somewhat slower than the mean wind speed. The coherency of the microfront decreases significantly below 20 m. Occasionally the microfront is first observed at the downstream tower hinting that a downward burst of momentum is tilted such that the phase appears to be propagating upstream as observed from a fixed point. Considerable refinement work is needed.

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